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HIGH PRESSURE GAS STORAGE CAPACITIES. EXAMPLE OF A SOLUTION USING FILAMENT WINDINGS.

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16. Abstract

The work described is based on the use of epoxy resin fiber glass. Economic factors affecting the choice of materials are discussed. Specific examples are treated: the physical nature of the windings are described together with the results obtained. The study demonstrates that a substantial reduction in mass and an enhanced level of safety can be assured at a competitive cost by storing gases in this way.

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We should like to recall that metallic reservoirs /2*
and metallic containers are presently widely used for storing high pressure gas.

The progress achieved in metallurgy and technology has greatly contributed to maintain this state. The performances of these reservoirs have been improved and costs have been reduced. For several decades, the following have appeared on the market: steel reservoirs, light alloy containers either reinforced with steel bands or not reinforced. Their storage capacity has increased (the service pressure has increased from 150 bars to 200 bars, then to 250 bars and soon it will be 300 bars).

It seems as though metallic containers do not have any serious competition in the market place. However, over the last three years using the technique of filament winding with non-metallic fibers, several solutions to the high pressure gas storage problem have been proposed especially in the United States. Presently, in the United States there are several types of high pressure containers which use this technique. It appears as though this technique will be widely used in the future, especially on the other side of the Atlantic. This technique has been widely used in ballistic and space applications and by using it, the users obtain better performance using new solutions.

However, there are still certain drawbacks associated with the solution and these speak against the use of them in the European countries especially. Should we overcome these drawbacks in our country and adapt the filament winding technique for storing high pressure gas?

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*Numbers in margin indicate pagination of foreign text.

At the SNIAS--Ballistic and Space Division, Aquitaine Facility, we answered this question with a yes. Our experience over more than 15 years in the area of wound filaments applied for pressure applications* were encouraging. Our experience covers methods of dimensioning, winding technology, and wound composites. We performed interesting studies about high pressure storage capacities which were encouraging. In the following we will present results. We hope that they will convince numerous users that at the present time there exists a thoroughly reliable technology for solving problems in this area, which is the filament winding technique.

The studies were concerned with two objectives: /3

a) demonstrate the interest in filament winding techniques applied to high pressure tanks.

b) verify this interest using concrete applications.

In order to achieve our first objective, we performed a parametric study about the performances of wound reservoirs and their costs without forgetting the safety aspects during use.

We assume the following hypotheses:

a) nominal service pressure: Pr = 350 bars
b) test pressure = Pe = 1.5•Pr = 525 bars
c) burst pressure = Pr = 2.5•Pr = 875 bars

The parameters studied were the following:

a) the reservoir volume (V)
b) the length to diameter ratio (L/D)
c) a completely wound version
d) a version wound on a metallic envelope
e) a wound version, wound only over the cylindrical part of the metallic envelope

* Such as the Diamant missile propulsion structure and ballistic vehicles.

In order to characterize the performances of high pressure tanks, we used the following quantity called the performance factor:

$$Fp = \frac{Vg}{Ms} \ (m3/Kg)$$

- Vg is the volume of the reservoir in m3 of gas brought to atmospheric pressure
- Ms is the mass of the reservoir in Kg

The results of our study in terms of the performance factor are given in Figures 1, 2, 3 and 4.

These results show that a substantial weight gain can be achieved with respect to classical metallic reservoirs, no matter what kind of wound version we study. This was predictable because any specific traction specific resistance of the fibers is much higher than for any metal.

This study is based on the use of a gas-resin epoxy fiber, but performance is improved substantially with the Kevlar fiber. /4

We are sure that reservations about these types of containers, which we discussed above, in part come from the fact that their cost is believed to be very high, because we are dealing with base technology, etc.

This certainly would have been true a few years ago when this technique still had to be mastered. However, it was only used for very special applications for a very small number of samples which were fabricated. However, the situation is different today. This technique is perfectly known and mastered. We know this because the SNIAS, more than 15 years ago, was the first company in France and in Europe to work on mastering the filament winding technique. Many successes have been achieved in this area. Obviously, mastering this technique implies a substantial cost reduction.

There is another factor which is no less important which also plays a role in substantially reducing the cost. This is the cost of raw material. Costs of the fibers are coming down compared with the price of metal. The fact that we can predict a mass production of these high pressure containers is a very favorable factor as well.

At the present time, the unit cost of mass produced containers using the filament winding technique is completely competitive, no matter what version is adapted.

It is certain that the use of high pressure wound containers will be entirely safe. Several factors support this:

- the reproducibility of the wound composite characteristics is very great (a few per cent dispersion)
- the composite materials have been known to support very well cyclical loads
- for wound versions on metallic envelopes, it is possible to dimension the unit such that the stresses induced in the metal at the service pressure only amount to a small fraction of the stress for 0.2% of extension. This is done without substantially aggravating the weight estimate. This is also favorable for supporting cyclical loads.
- for the same versions, we will see that the extensions induced in the metal at the test pressure are greater than the elastic extension. This allows us to eliminate containers which have fabrication cracks in the metallic envelope.
- the global strength implies a large number of wound layers /5
  and, therefore, the effect of surface deterioration is not great. The fracture of these reservoirs occurs without any fragments.

We will discuss the details using two examples of application developed at the present time at the Aquitaine Facility of the

National Industrial Aerospace Society.

The first case* illustrates what one can obtain from filament winding technique in applications where the weight gain is an important criterion, but where the cost has to remain competitive with the cost obtained using classical techniques using only metallic materials.

These cost considerations made us eliminate high performance fibers which are still expensive, such as Kevlar.

The technical specifications which we will present led us to adapt an internal light alloy metallic envelope** for reasons associated with sealing problems and compatability problems with the stored fluid.

Following are the specifications:

- volume capacity = 30 l
- service pressure = 350 bars
- test pressure = 525 bars (a coefficient of 1.5 with respect to the service pressure)
- burst pressure > 875 bars (2 times and a half the service pressure)
- stored fluid = Air, nitrogen***,...
- lifetime: 10 years
- number of compression-decompression cycles = 10,000

The conclusions of the parametric study which will be

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*Which is derived from the parametric study which we discussed.

**A principle which also supports economy because in this case, the internal metallic envelope also serves as a winding mandrel.

***CO_2 + nitrogen, oxygen and hydrogen.

presented further on led us to select a diameter-to-length ratio of 1/4.

Finally, for safety reasons, the capacity must be calculated so as to fracture along a sleeve or a generator. /6

Let us now consider the development steps and the results.

First of all, we selected the raw materials:
- fibers,
- resins,
- metal.

The fiber selected was due to its performance price ratio and its good aging characteristics, the type R fiber*.

The resin adapted is an epoxy resin because of its handling qualities and its good aging properties.

The selection of the metal was dictated according to the following criteria:
- capacity for elongation for biaxial traction,
- fatigue characteristics,
- resistance to corrosion under tension,
- compatability with stored fluids,
- specific resistance,
- forming characteristics.

After we had made these selections, the study bureau carried out a preliminary dimensioning analysis of the capacity and especially determined the thickness of the internal metallic envelope.

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*Glass E, even though it is less expensive, was eliminated because of its poor aging characteristics.

This thickness is determined by taking into account that, because of the large elongation of the glass-resin composite, the metal for the most part exceeds its elastic limit during the testing operation. Consequently, it will be in a state of compression when it is returned to zero pressure.

After testing, the entire structure has a perfectly elastic behavior and at service pressure, the load in the metal remains far away from the load it experienced during testing. The dimensioning, therefore, has to take into account this difference, which has to be selected as a function of the number of cycles which the structure has to withstand. /7

During this preliminary stage, that is, predimensioning of the thickness of the metallic wall, the bureau was able to perform the following:

- first of all, perform a preliminary working drawing of the internal metallic envelope. After examination of the production services and after fabrication tests, and after evaluating its pressure resistance, it was given a definite form,
- also the dimensioning activity was concluded by establishing the characteristics of the windings. For this, we fixed the characteristics of the longitudinal members.

The strength of the structure of a filament composite is a function of the angle α between the thread and the meridian. In the case of flat winding, the angle α is fixed by the geometry, as we will see in the top figure*, However, values can be much greater in the case of helicoidal winding as in the lower figure*.

This angle must be selected so that, taking into account the opening diameters and the cylinder diameter as well as the shape of the base, the trajectory of the thread over them will approach as much as possible an isotensoidal geodesic. In the case under

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* (Figure 5)

consideration, this then leads to the requirement for helicoidal winding.

When the winding technique and the angle α are fixed, it is then easy to calculate the roving thickness which is necessary in order to equalize the longitudinal traction flux due to pressure. In the first stage, the calculation is performed at the predicted burst pressure ignoring the resistance of the resin. In order to take into account the requirement for preferentially fracturing along a generator, a reduction coefficient for the fracture resistance of the fiber will be applied. Since the metal is in a plastic phase, it is assumed that its participation in the resistance of the entire unit is reduced to the product of its limit elastic stress and its thickness. This then results in the following formula for the thickness of the longitudinal composite:

$$Efl = \frac{Pc.R - 2.\sigma_{0,2}.em}{2.\sigma_{flc}.\cos^2\alpha}$$

- After Efl has been determined, it is found that at the service pressure, the stress in the metal does not exceed the value derived from the number of cycles which the structure has to be capable of withstanding. It is also found that after testing, one does not achieve a prohibitive compression stress when the pressure is returned to zero. /8

Then, one proceeds with the calculation of the composite thickness to be deposited in the circumferential direction. This calculation is made from results of the determination of the metal thickness and the longitudinal composite thickness. It is to be recalled that the participation of the composite in the circumferential resistance is limited to:

$$\sigma_{flc}.efl.\sin^2\alpha$$

Just like for the longitudinal calculation, first of all, the burst pressure is evaluated and then one verifies that

the hypotheses for the service pressure and the test pressure have been satisfied.

Once this predimensioning has been carried out, one performs a winding stability test on a model and one optimizes the angle α, which then brings about a new verification of the dimensioning process. This is then compared with the preliminary calculations. Also the following have to be considered:

1) One wishes a higher safety coefficient in the longitudinal direction than in the circumferential direction. Therefore, the metal stresses were modified, which during the first part of the study, were assumed to withstand a biaxial load with equal extension.
2) The presence of the resin and its degradation, or the degradation of the resin/fiber during testing.
3) Overstresses are possible in the binding zones. These overstresses are caused by the fact that it is not possible to have a perfectly isotensoid trajectory, in order to satisfy the requirements for winding and the global geometry requirements for the structure (openings AV and AR are not equal, ratio of the opening ϕ and the collar ϕ are increased).

Once this work is carried out and the quantities have been defined, work on the container proceeds in two directions:

1) An industrial study about production means, fabrication techniques, so as to reduce costs to a minimum.
2) A series of tests allows one to evaluate the performance of the container and its relationship with the load log for which it was defined.

These tests cover the following:

1) Only the internal metallic envelope.
2) The reduced circumferential dimensions in order to evaluate the capacity of the bases and the longitudinal windings.
3) The subsequent nominal capacity.

This is all done with non-aged specimens. /9

Qualification tests are selected as a function of the applications and then cyclic tests are performed.

For the container for which we have presented a technical data sheet, and the definite dimensions are given in Figure 6, let us now compare the results obtained with those for completely metallic structures.

The Table of Figure 7 shows the mass advantage obtained, and no discussion is needed.

The second case which we will now discuss is the case of a pressure vessel designed for a spacecraft or an aircraft.

For this application it is obvious that the mass gain is the most important factor, the mass gain over a metallic unit.

Therefore, we decided the following:

1) Use of a very high performance fiber, Kevlar 49.
2) Replacement of the internal metallic envelope by an internal elastomer unit which is solely used to provide sealing of the structure.

Its data sheet shows that we are dealing with a very small object.

- useful volume: 1.1 liters
- external diameter: 116 mm

- overall length: 280 mm

However, its burst pressure is less than 1100 bars, and the high performance level as well as its large opening diameter and collar diameter ratio justify our interest in this study.

This ratio of opening diameter to collar diameter is large as can be seen (Figure 8) and the asymmetry between the opening diameters, AV and AR mean that it is difficult to obtain this kind of winding and the base shapes, compared with what can be achieved with an isotensoid geodesic trajectory. The correct dimensioning of the longitudinal members has to take into account the over-stresses which the particular geometries induce in the base areas. In contrast to the container discussed above, they are very large. The mathematical solution to this problem is outside the scope of this article. For information purposes, it should be realized that the fracture base pressure (the unit was purposely given an excessively large collar) of the first unit tested was 1160 bars compared with 1150 bars obtained from theory. It should be realized that this first test was performed after a preliminary test. This agreement between the calculated pressure and the measured fracture pressure, therefore, for the most part validates the method used. /10

After this we will not discuss the development processes which were performed, because they are similar to what we discussed for the first example, except for calculations and experiments related to the internal metallic envelope and which is not needed in this case.

On the other hand, it is interesting to compare the recorded performance with that of a steel vessel which it replaces, that is,

- wound vessel mass 2600 grams, out of which 1630 g is a metal tip
- high limit elastic steel vessel mass corresponds to 4500 g.

Conclusion:

This study allowed us to show that the filament winding technique is interesting for solving high pressure gas storage problems. A very substantial mass gain is achieved, safety is insured and the cost is competitive.

We hope that several users will share our convictions, especially those which are still skeptical.

J. LAMALLE A. PHAN

FIGURE 1. Graph F as a function of L/D - Solution I

- completely wound vessel made of epoxy glass-resin
- sealing provided and appropriate flanges
- F = number of m^3 of gas/vessel mass

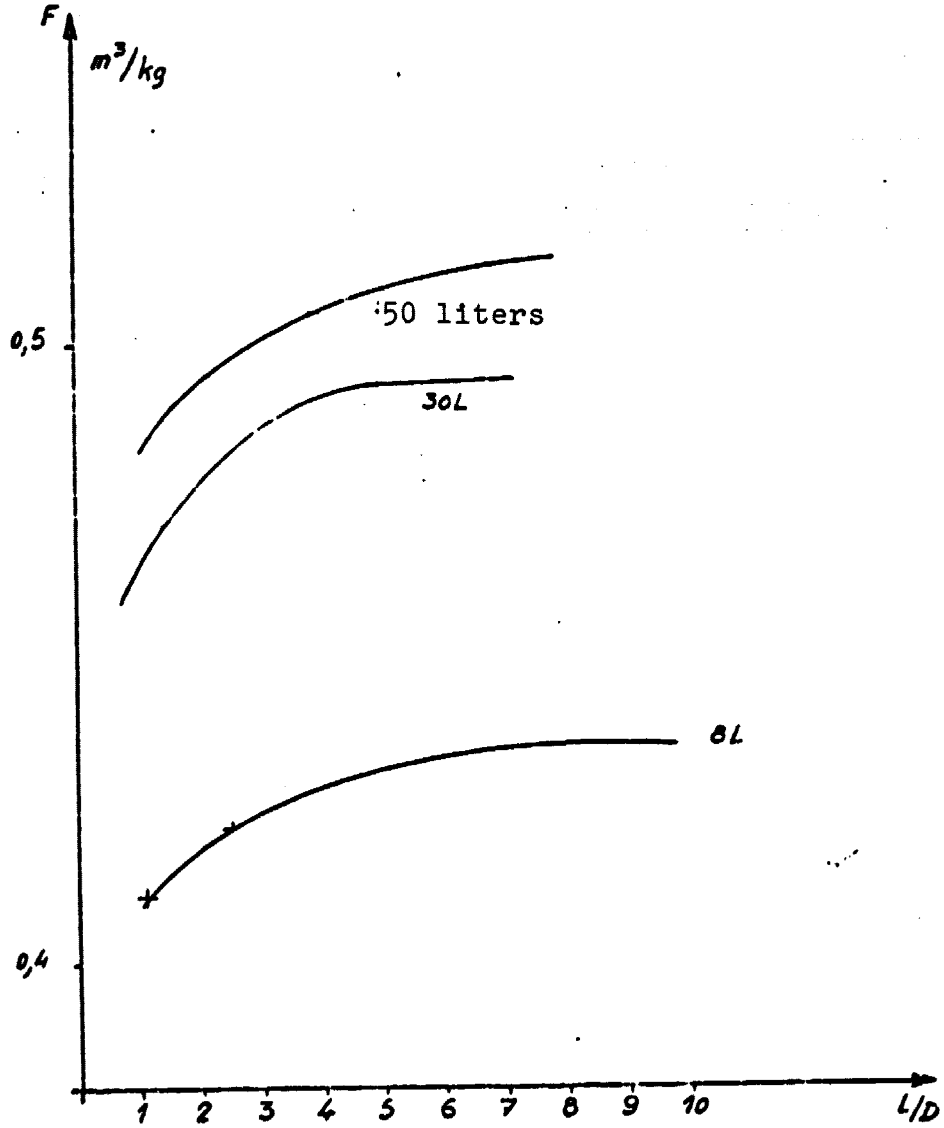

FIGURE 2. Graph F is a function of L/D - Solution II

- Metallic vessel (steel or light alloy) completely reinforced with winding (epoxy glass-resin)

  F = number of m^3 of gas/vessel mass

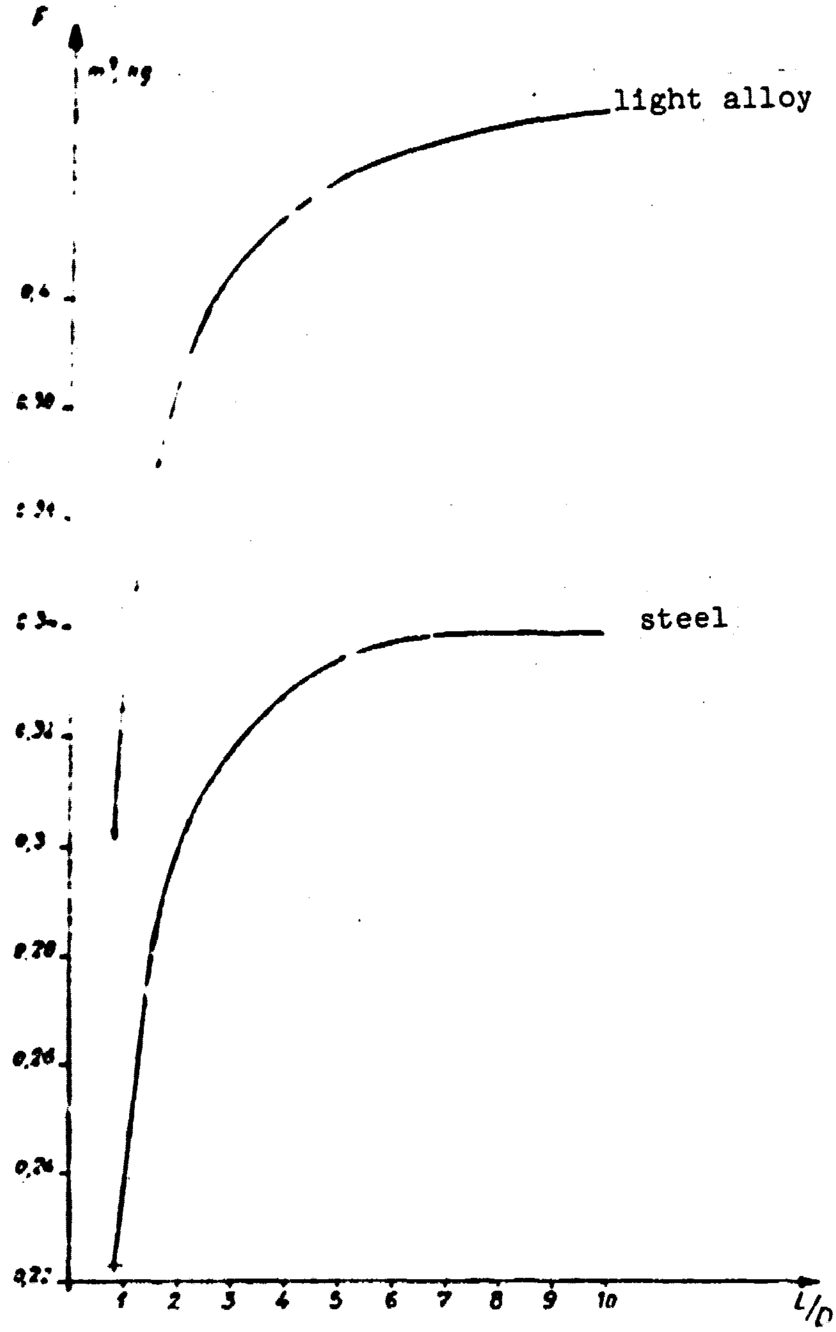

FIGURE 3. Graph F is a function of L/D - Solution III

- Metallic vessel (steel or light alloy) reinforced only over the cylindrical part using winding (epoxy glass/resin)

  F = number of m^3 of gas/vessel mass

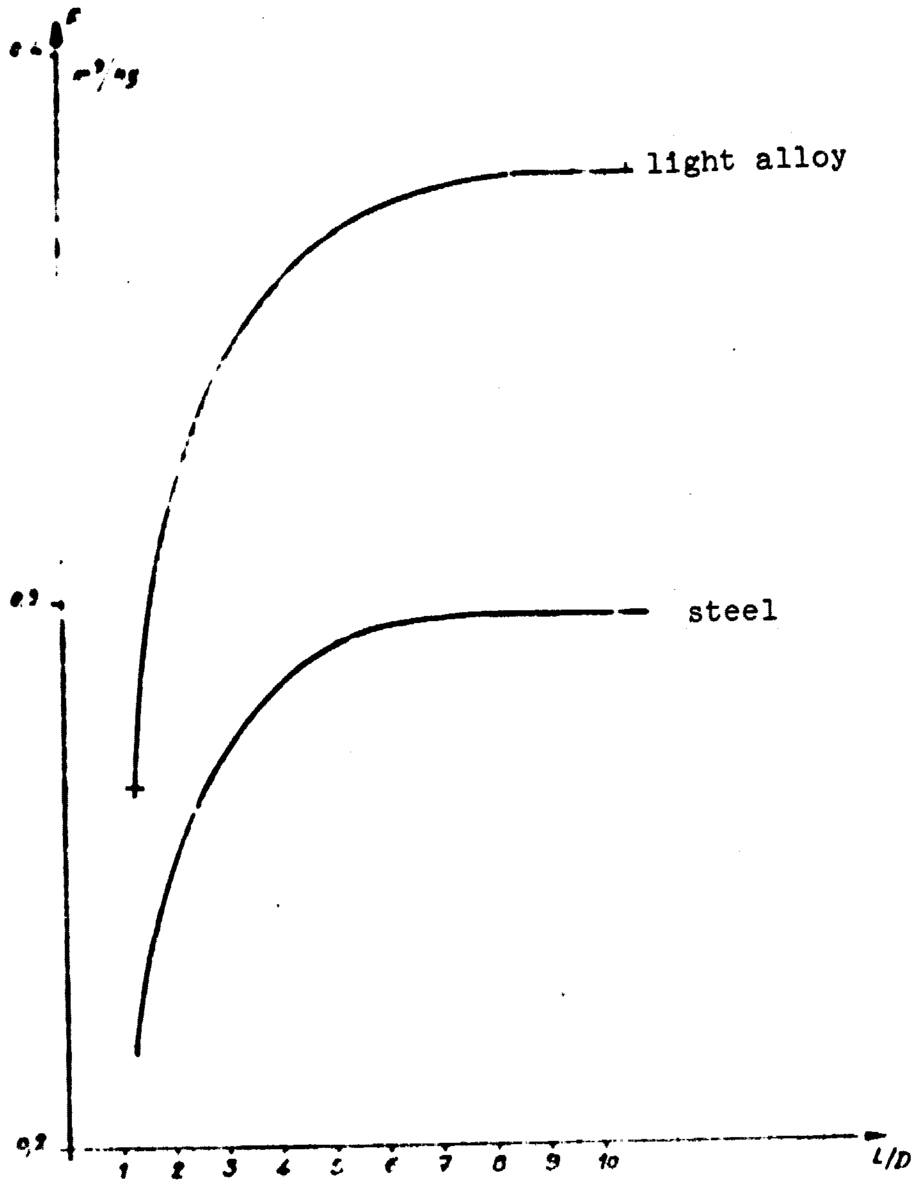

FIGURE 4. Performance Factor F

F = number of m^3 of gas/vessel mass

variation of F due to different dimensional characteristics

(1) existing commercial units

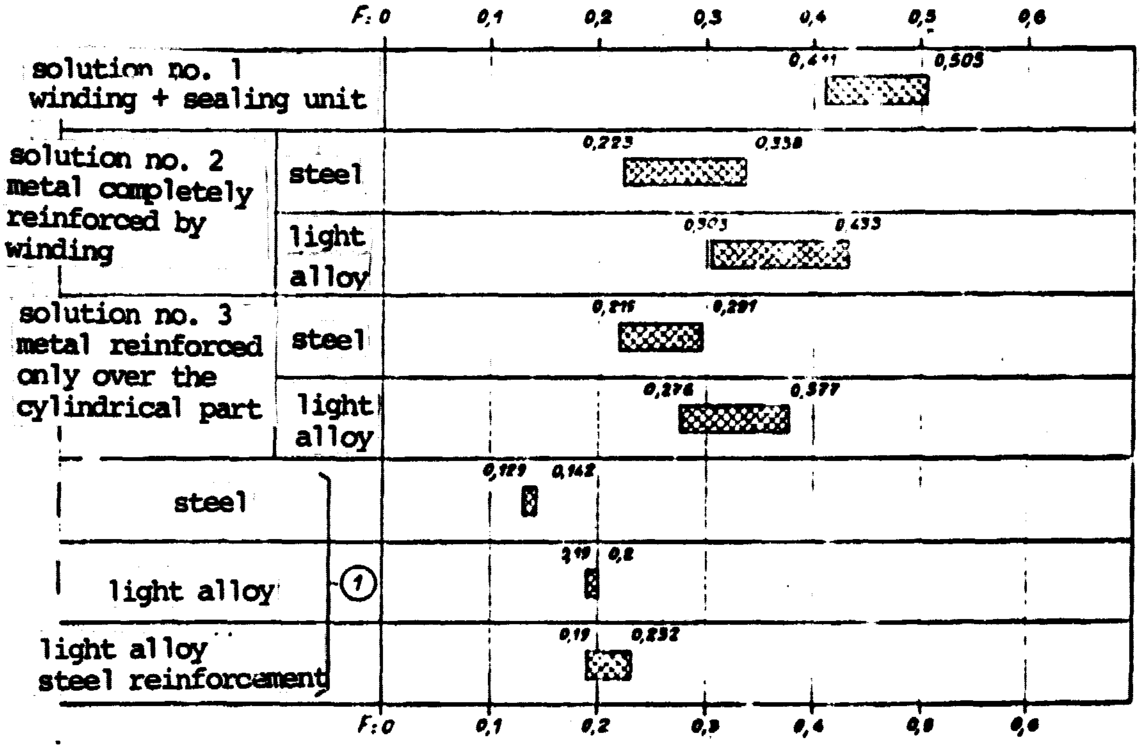

FIGURE 5. Winding Types

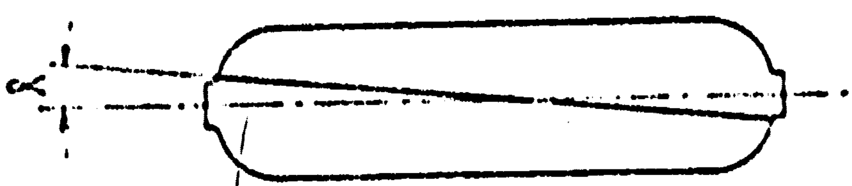

Fig. a plane winding

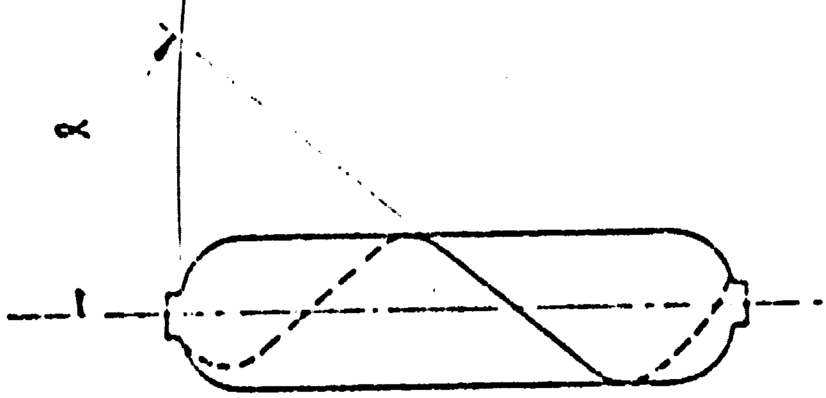

Fig. b - helicoidal winding

FIGURE 6. High pressure vessel type 30L-875 b

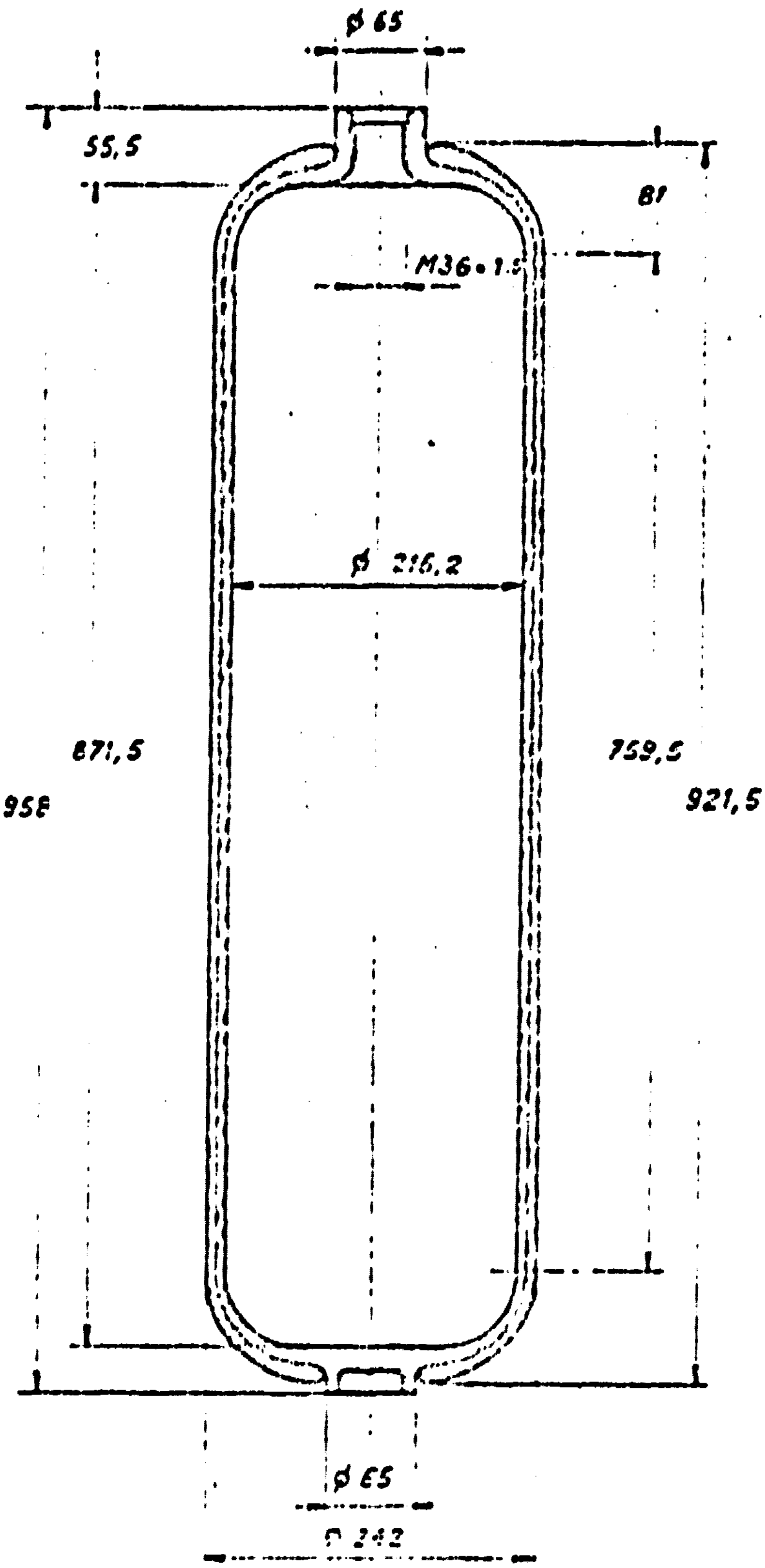

FIGURE 7. High pressure vessel type 30L - 875 b

Performance Comparison

	structure with metal envelope reinforced with composite	completely metallic structure: light alloys	completely metallic structure: steel
service pressure	350 bars		
burst pressure	875 bars		
interior volume	31,36 litres		
internal diameter	108,4 mm		
internal length	871,5 mm		
composite mass	11 Kg		
metal mass	14,6 Kg	51 Kg	73 Kg
total mass of the structure	25,6 Kg	51 Kg	73 Kg

ratio of performance factors = $\dfrac{\text{metallic reinforced vessel}}{\text{metallic vessel}}$

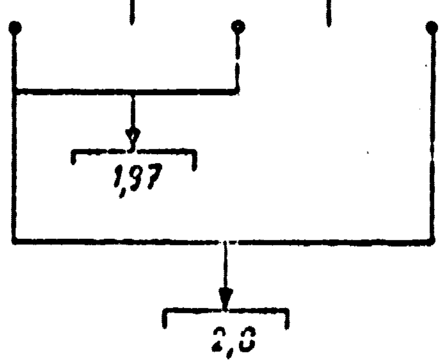

FIGURE 8. High pressure vessel type 1.1L - 1100 b